Estimate of the Tevatron vacuum on the basis of the known pressure rise at F11

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Introduction

It has been discovered recently that the vacuum pressure in F11 rises drastically over the first few hours of every Tevatron store – see Figure 1. One can see that the F11 vacuum pressure rise is responsible for about 30-40% of CDF's proton-related background rate. It also sets the scale of the average (integrated over the ring) vacuum variation.

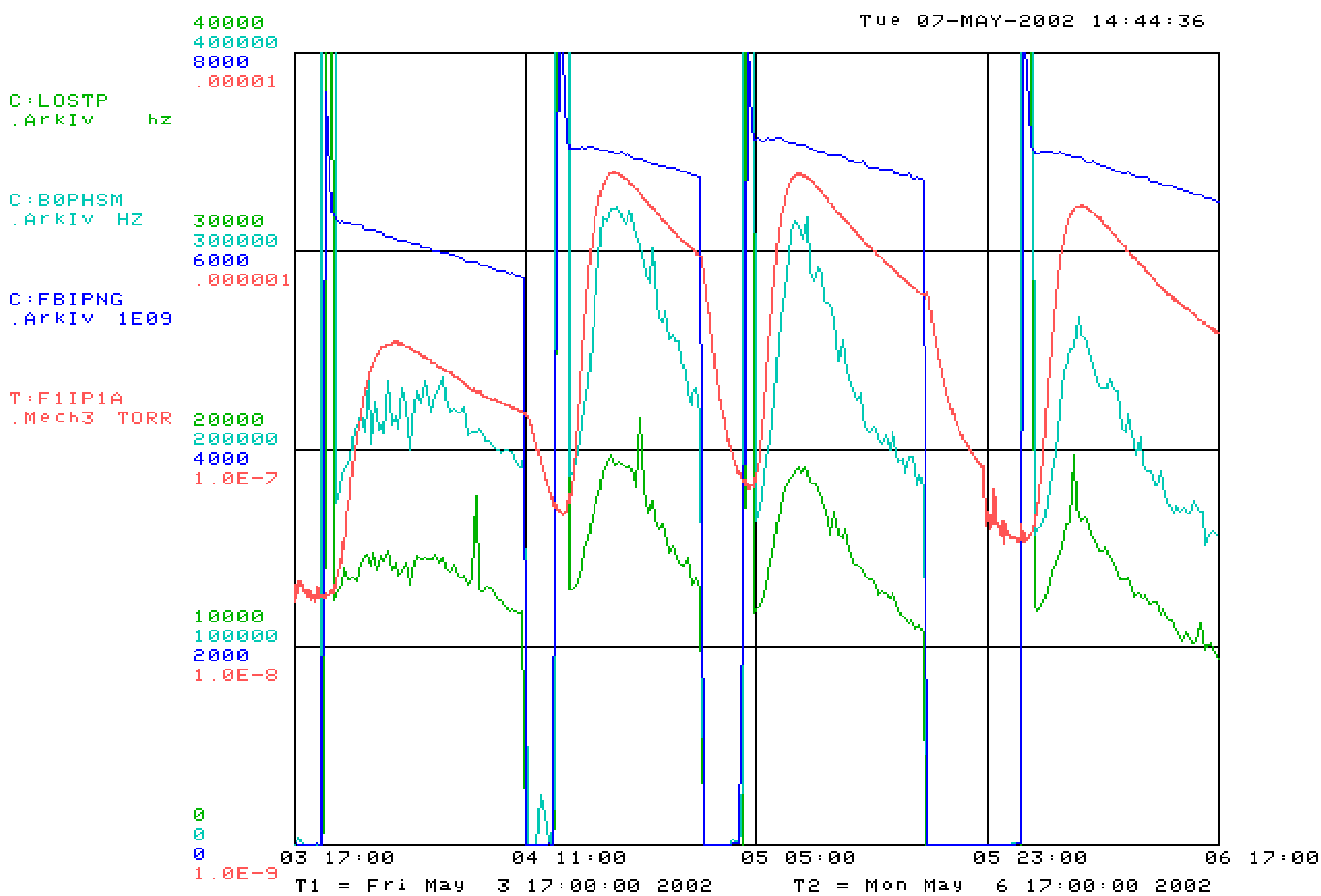

Figure 1: Correlation of CDF proton halo losses and F11 pressure over several stores. In green is C:LOSTP (CDF proton halo loss counter), cyan is C:B0PHSM (another CDF proton halo loss counter), blue is C:FBIPNG (narrow gate proton bunched-beam intensity), and red is T:F1IP1A (pressure reading from an ion pump in F11).

1. Proton Lifetime

The F11 vacuum affects not only the CDF background, but also the proton lifetime. Figure 2 shows that the proton loss rate (determined by differentiation of the total DC beam current – ACNET variable T:IBEAM) varies with time in the store 1207 in quite the same fashion as the F11 vacuum pressure. A simple fit gives an approximate relation between the total Tev beam loss rate and the pressure:

$$-dN/dt\ [e12/hr] = 0.035 + P_{F11}\ [Torr] * 10000 \quad (1)$$

where P_{F11} is measured at a local ion gauge, max 1.5e-6 Torr. One can estimate the average Tevatron vacuum if the local integrated vacuum load at F11 is determined.

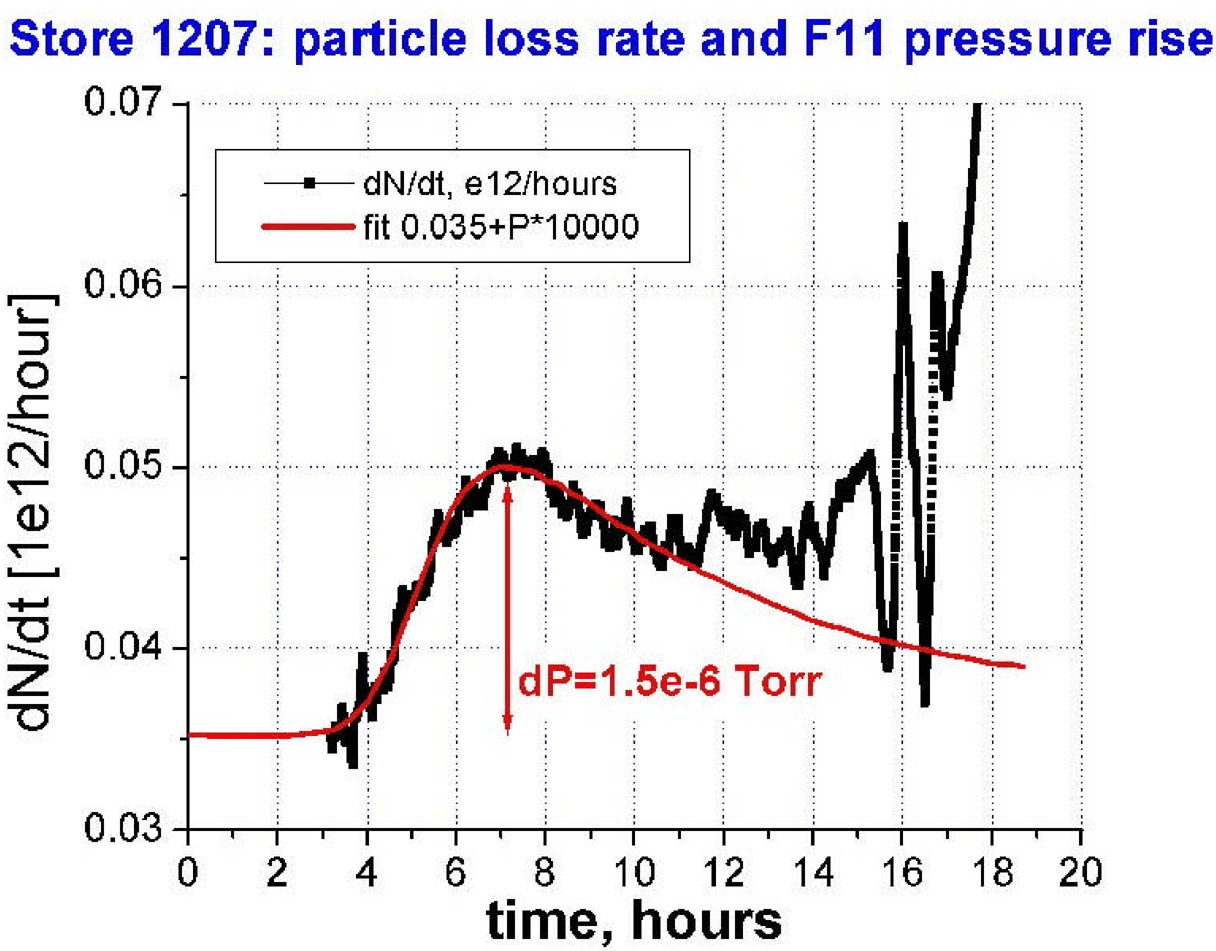

Figure 2: Proton loss rate and F11 pressure rise versus time.

2. Pressure Model

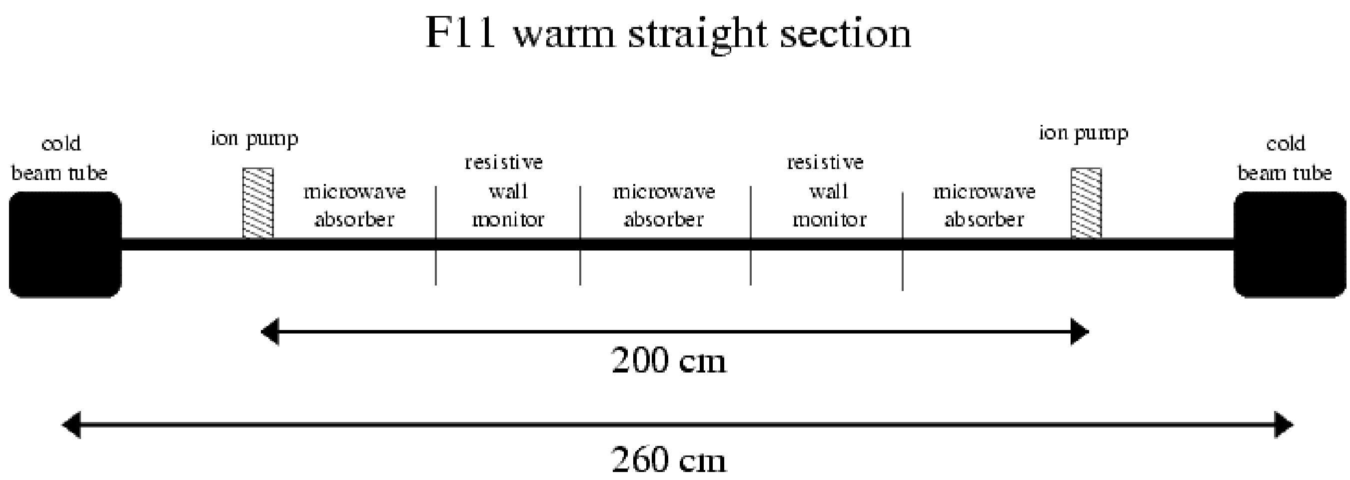

Figure 3: Schematic of the F11 warm straight section.

The F11 straight section is depicted in Figure 3. The total length of this warm section, from the cold beampipe on one side to the other, is approximately 260 cm. The beampipe has a round cross-section of radius $R = 3.65$ cm. There are two 20 L/s ion pumps approximately 200 cm apart which also provide pressure measurements. Between the ion pumps are 3 sets of microwave-absorbing ferrite rods and 2 resistive wall monitors. The wall monitors are the beam pick-up devices for the Sampled Bunch Display (SBD) and the Mountain Range displays.

We hypothesize that outgassing of material (especially the ferrite rods) within the beampipe causes the vacuum degradation in F11 during HEP stores. To estimate the maximum and average pressures based on the reported ion pump pressures, we have developed a simple model of the F11 section pressure profile. In our model, we assume a uniform outgassing rate over the span between the two ion pumps. The beampipe between the ion pumps and the cold sections is assumed to have a negligible outgassing rate. We also assume that the cold beam tubes act as high speed “black hole” orifice pumps. For our calculations, we assume the outgassed material is N_2 (mass = 28 amu) at a temperature of 300 ºK.

The pressure profile between the ion pumps is obtained by solving the equation $\frac{d^2P}{dx^2} = -\frac{a}{c}$ where a is the specific outgassing rate in $\mathrm{torr} \cdot \frac{\mathrm{L}}{\mathrm{s}} \frac{1}{\mathrm{m}}$ and c is the specific conductance in $\frac{\mathrm{L}}{\mathrm{s}} \cdot \mathrm{m}$. Here, $x = 0$ is the midpoint between the ion pumps located at $x = \pm L/2$ (L=2m). Assuming the pressures reported by the ion pumps are both equal to P_0, the pressure profile is:

$$P(x) = P_0 + \frac{1}{2}\frac{a}{c}\left(\frac{L^2}{4} - x^2\right) \qquad (2)$$

Now, we need to determine a and c to complete our pressure profile between the ion pumps. The conductance of the beampipe is given by:

$$C_{pipe} = \frac{1}{1 + \frac{3}{8}\frac{L}{R}} \frac{\langle \mathrm{v} \rangle}{4} pR^2 \qquad (3)$$

where $\langle \mathrm{v} \rangle$ = 478 m/s is the average molecular velocity for N_2 at 300 ºK, L = 200 cm is the length of the section and R is the beampipe radius. The above parameters give a beampipe conductance of C_{pipe} = 23.2 L/s and specific conductance c = 46.4 $\frac{\mathrm{L}}{\mathrm{s}} \cdot \mathrm{m}$.

The specific outgassing rate can be estimated by knowing the pressure P_0 and the effective pumping speed S_{eff} at an ion pump. The pressure is related to the effective pumping speed and the outgassed molecular flux Q by $P_0 = Q/S_{eff}$. At one ion pump, we can estimate $Q = a \cdot L/2$, so we can determine a in terms of the pressure and effective pumping speed: $a = 2\frac{P_0 S_{eff}}{L}$.

What is the effective pumping speed S_{eff} at the ion pumps? In addition to the actual pumping speed of the ion pumps, we must consider the speed of the "black hole" pump arising from the cold beam pipe. The conductance of such an orifice (in L/s) is given by $C_{BH} = 3.64 A\sqrt{T/M}$, where A is the cross-sectional area of the orifice, T is temperature in ºK, and M is molecular weight in amu. Using the stated parameters, we obtain C_{BH} = 500 L/s. However, $C_{pipe} << C_{BH}$ (122 L/s for the 30 cm long piece of pipe

<< 500 L/s), so the beampipe conductance limits the actual pumping speed of the orifice at the ion pump. Consequently, the conductance of the orifice plus beampipe combination at the ion pump is only $S' = 1/(1/C_{pipe} + 1/C_{BH})$ = 98 L/s. Combining this pumping speed in parallel with the actual ion pump speed, we get $S_{eff} = S_{IP} + S'$ =118 L/s. Substituting $a = 118\, P_0$ L/s/m and c = 46.4 L/s*m in Eq (2), we obtain:

$$P(x) \approx P_0\left[1 + 1.27 \cdot \left(1 - (x/1\,\mathrm{m})^2\right)\right] \qquad (4)$$

The maximum pressure occurs at $x = 0$, and $P_{max} = 2.27\, P_0$. The average pressure between the ion pumps is $P_{avg} = 1.85\, P_0$.

The pressure profile between the ion pumps and the "black hole" pumps falls linearly from the ion pumps since we assume no outgassing there. Solving $\frac{d^2P}{dx^2} = 0$ and using the known values of the beampipe and orifice conductances, we see the approximate pressure profile here is: $P_{avg} = P_0\,(1 - x/30\ \mathrm{cm})$ where $x = 0$ is the position of an ion pump and x = 30 cm is the orifice pump (start of cold beampipe). Here, the maximum pressure is P_0, and the average pressure is $P_{avg} = 0.52\, P_0$.

We can now calculate the average pressure throughout the F11 straight section based on the pressure readings from the ion pumps. Weighting the above average pressures from each section by the appropriate lengths, we see:

$$P_{avg} \approx \frac{1}{260\ \mathrm{cm}}\left(1.85\, P_0 \cdot 200\ \mathrm{cm} + 0.52\, P_0 \cdot 2 \cdot 30\,\mathrm{cm}\right) \approx 1.54\, P_0 \quad (5)$$

So, if the ion pump pressure is $P_0 = P_{F11}$ =1.5[μTorr], the maximum pressure in F11 is actually P_{max} =3.40 [μTorr], and the average pressure is $P_{avg} = \langle P_{F11} \rangle$ = 2.31 [μTorr].

3. Average Tevatron Vacuum Pressure

Using the average pressure over L_{F11}=2.6m is $\langle P_{F11} \rangle$=2.31e-6 Torr, we can rewrite Eq.(1) as:

$$dN/dt\ [e12/hr] = 0.035 + \langle P_{F11} \rangle\ [Torr]\ L_{F11}\ [m] * 2500 \qquad (6).$$

Recent studies of the CDF losses suggest that vacuum contributes about 2/3 into the total beam loss (another 1/3 is due to particles leaking out of RF buckers – A.Tollestrup, presented May 31, 2002 at the Tev Dept Meeting). Based on that, one can estimate an equivalent average Tev vacuum pressure as

$$dN/dt\ [e12/hr] = 0.035/3 + (\langle P_{TEV} \rangle C + \langle P_{F11} \rangle L_{F11}) * 2500 \qquad (7)$$

Comparing Eq.(7) with Eq.(1), one gets

$$\langle P_{TEV} \rangle = 2/3 * 0.035 / C[m] / 2500 = 0.023 / 6280 / 2500 = 1.5e\text{-}9 \text{ Torr} \qquad (8)$$

“Equivalent” assumes: a) that gas content around Tev is the same as in F11, which is not necessarily true, and b) gas temperature in Tev is the same as in F11 (what affects dN/dt is *gas concentration* not pressure) – that is surely not true as the most of the Tevatron is cold.

4. Comparison with Theory

“Handbook of Accelerator Physics and Engineering” (World Scientific, 1998, p. 215) gives an estimate of beam lifetime for room temperature vacuum consisting of N_2 molecules:

$$1/\tau_{gas}[s] = 1/N\ dN/dt = 870\ \langle P_{TEV} \rangle\ [\text{Torr}] \qquad (9).$$

Using N = 7600e9 and $\langle P_{TEV} \rangle$ = 1.6e-9 Torr gives an estimated loss rate of dN/dt = 9.9×10^6 [1/s] = $0.036 \cdot 10^{12}$ [1/hr]. The latter number is about 50% greater than the measured rate of $0.023 \cdot 10^{12}$ [1/hr] used above. Such agreement can be considered satisfactory.

Eq.(13) on page 277 of the same reference estimates transverse normalized emittance growth (in FNAL units of 95% emittance) due to scattering on gas molecules which are assumed to be air:

$$d\varepsilon_N/dt = 6\langle\beta\rangle\ (1.6\cdot 10^{-7}\ 1/s)\ \langle P_{TEV}\rangle\ [\mu Torr] / \gamma \qquad (10).$$

For $\langle\beta\rangle$ = 70 m, $\langle P_{TEV}\rangle$ = 1.6e-3 μTorr, and γ = 1044, we get $d\varepsilon_N/dt$ = 0.35 πmm mrad /hr, is within the spread of experimentally observed rates 0.3-0.6 πmm mrad /hr (see, e.g., minutes of Tev Dept Meeting on 04/26/02). As we mentioned in the introduction, the F11 vacuum load changes the average Tevatron vacuum by some 30-40%, so one expects to see the same increase in $d\varepsilon_N/dt$. Unfortunately, Synchrotron Light Monitors, the only non-disruptive Tevatron beam size diagnostics, does not show such an increase – probably because the instrument did not operate reliably at that time.

5. Discussion/Future Work

The estimate of the Tevatron vacuum based on correlation between the measured pressure rise at F11 and proton loss rate is some 3 times less than the Tevatron vacuum pressure estimated from the emittance growth at 150 GeV $\langle P_{TEV}\rangle$ = 4 e-9 Torr (equivalent for Nitrogen molecules) – see studies performed by V. Lebedev on 04/12/2002. He observed $d\varepsilon_N/dt$ = 4.8 πmm mrad /hr at 150 GeV (that is equivalent to 0.73 πmm mrad /hr at 980 GeV – that number which marginally agrees with the worst store observations). We need to understand this discrepancy.

Obviously, the estimate says that the Tevatron vacuum is very bad – for comparison, average vacuum pressure in the Antiproton Accumulator is about $\langle P_{AA}\rangle$= 7 e-11 Torr, or more than 20 times better than in the Tevatron. Distribution of the Tevatron vacuum pressure has to be understood and proper measures have to be taken to improve the vacuum. We believe that a factor of 2-3 improvement in the average vacuum is possible by the end of 2002.